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RESEARCH MEMORANDUM

IGNITION-DELAY CHARACTERISTICS IN MODIFIED OPEN-CUP APPARATUS OF SEVERAL FUELS WITH NITRIC ACID OXIDANTS WITHIN TEMPERATURE RANGE 70° TO -105° F

By Riley O. Miller

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

IGNITION-DELAY CHARACTERISTICS IN MODIFIED OPEN-CUP APPARATUS OF SEVERAL FUELS WITH NITRIC ACID OXIDANTS WITHIN TEMPERATURE RANGE 70° TO -105° F

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SUMMARY

Ignition-delay characteristics of approximately 90 fuel-oxidant combinations were determined in a modified open-cup apparatus at -40° F. Combinations considered worthy of further study were investigated at temperatures in the range 70° to -105° F. Freezing temperatures of acids were determined as well as viscosities of several fuels at moderate and low temperatures.

At -40° F, several blends of aromatic amines with triethylamine show promise as ignitor fuels with mixed acid (nitric acid plus sulfuric acid) and red fuming nitric acid, and some of these fuels may be useful also with white fuming nitric acid.

Several blends of aromatic amines in triethylamine were found to be fluid at -105° F and red fuming nitric acid containing approximately 3 percent water and 19 percent nitrogen tetroxide was found to freeze at approximately -87° F. With this acid, 30 percent by volume blends of o-toluidine, aniline, and xylidines, respectively, in triethylamine showed desirable ignition characteristics at -76° F, specified maximum freezing temperature for military aviation fuels. With this red fuming nitric acid supercooled to -105° F, 30 percent by volume o-toluidine in triethylamine showed the most consistent ignitibility.

INTRODUCTION

The tactical application of rocket power plants may be considerably extended when fuel-oxidant combinations are available that are fluid and self-igniting at very low temperature. A primary use for these fuel-oxidant combinations will be in booster rockets for aircraft flying at high altitudes because repeated starts will be required and each start must be quick and reliable. Reliable low-temperature starts will be required also of air-to-air and air-to-surface rocket missiles, and rockets used under arctic conditions.

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For economic and logistic reasons, nitric acid oxidants are favored for rocket applications in which propellants are to be stored several months. Mixed acid (nitric acid plus sulfuric acid), red fuming nitric acid (nitric acid plus nitrogen tetroxide), and white fuming nitric acid have been used for this purpose. Recent investigations (references 1 to 3) have shown that several fuels will ignite with mixed acid at temperatures of -40° C and lower. Mixed acid, however, has the disadvantage of possible sludge formation during storage (reference 4); other types of nitric acid may therefore be preferred. Data of reference 3 and recent experiments at this laboratory, however, have shown that certain fuels which ignite with mixed acid at -40° F do not ignite satisfactorily with other acids at this temperature. A further investigation of ignitor fuels for use with several types of acid at -40° F was therefore in order.

The temperature -40° F has been used by several investigators as a standard low temperature for ignition-delay experiments and may be low enough as a minimum starting temperature for certain rocket applications. Lower temperatures, however, have been specified for military aircraft fuels and equipment. The freezing temperature for military aviation gasolines and jet-propulsion fuels is currently specified in references 5 and 6 to be not higher than -76° F (-60° C), and a minimum design temperature of -103° F (-75° C) is recommended in reference 7 because of very low temperatures occurring at high altitude in tropical regions. A need for investigation of fluid properties and ignition characteristics of fuel-oxidant combinations at temperatures at least as low as -76° F was apparent.

The investigation, described herein, was conducted at the NACA Lewis laboratory: (a) to select fuels which are fluid at low temperatures and will ignite at -40° F with mixed, red fuming, and white fuming nitric acids; and (b) to select a nitric acid oxidant which has a final freezing temperature that is lower than -76° F and will ignite several low viscosity fuels at -76° F and lower. Fuels were investigated with a view toward their utility either as rocket propellants or as ignitor fluids to initiate combustion of hydrocarbon fuels with an acid oxidant which could be used as a propellant in either case.

The viscosities of 24 fuels, the approximate freezing temperatures of 16 acids, and the ignition-delay characteristics for 93 fuel-oxidant combinations are presented herein. Ignition-delay data were obtained in a modified open-cup apparatus similar to that described in reference 2 except that improved instrumentation was incorporated.

OXIDANTS AND FUELS

Oxidants

Several mixed, red fuming, and white fuming nitric acids were investigated. The approximate freezing temperatures, compositions, and histories of these oxidant acids are presented in table I.

A code system is used herein to designate the several acids. The letters of the code symbol indicate the type of acid, that is: MA, mixed acid; RFNA, red fuming nitric acid; WFNA, white fuming nitric acid. The first number in the symbol always indicates the approximate percentage of water and the second number (when used) indicates the approximate percentage of either sulfuric acid in mixed acid or nitrogen tetroxide in red fuming nitric acid. Thus the symbol MA-2-17 designates a mixed acid with 2 percent water and 17 percent by weight sulfuric acid; RFNA-3-19, a red fuming nitric acid with approximately 3 percent water and 19 percent nitrogen tetroxide; and WFNA-7, a white fuming nitric acid with 7 percent water. Several special white fuming nitric acids containing other additives were also used. For these acids, the percentage of additive, indicated by a number, and the chemical symbol of the additive are given in parentheses following the basic symbol; thus, WFNA-8(6-KNO_3) is a white fuming nitric acid containing 8 percent water and 6 percent potassium nitrate. Three lots of red fuming nitric acid containing 2.2 to 3.0 percent water were designated RFNA-3-19 and the lot is indicated in several instances as lot a, b, or c, respectively.

Fuels

In most of this investigation fuels were used that were blends of aromatic amines in triethylamine. Data were also obtained using blended or unblended furan compounds, mercaptans, various unsaturated compounds, and hydrazine hydrate. The purpose of blending was (a) to produce fuels which were more fluid than the active component alone; and (b) to investigate further the possibility of producing blends with desirable ignition characteristics, inasmuch as certain blended fuels have been shown to ignite more satisfactorily than the parent constituents (references 2, 3, and 8).

The Shell Development Company supplied the following compounds: allyl glycidyl ether, 2-methylpentadiene, 2,2,4,6-tetramethyldihydropyridine, 3-mercapto-1-propanol; they also furnished physical-chemical data. The mixed butyl mercaptans and N,N-diallylaniline were supplied by the California Research Corporation through an arrangement with the Bureau of Aeronautics, U. S. Navy.

PROCEDURE AND APPARATUS

The experimental work may be divided into two phases, (a) measurement of physical and chemical properties of propellants, and (b) measurement of ignition delays of fuel-oxidant combinations.

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Measurement of Physical and Chemical Properties

Analysis of acids. - Red fuming, white fuming, and anhydrous nitric acids were analyzed according to the method of reference 9. Sulfuric acid in mixed acid was determined as barium sulfate. The compositions of several acids were calculated from the quantities of material added to the acid and notation has been made in such cases (see table I).

Freezing temperatures of acids. - Approximate freezing temperatures of acids were obtained by first freezing 20 milliliters of the acid in a thick walled 1- by 8-inch test tube, and then slowly warming the acid and noting the temperature at which cloudiness disappeared. A total-immersion toluene thermometer was used to measure temperatures and was calibrated under the conditions of the experiment with a standard iron-constantan thermocouple.

Viscosities of fuels. - Viscosities of fuels were obtained by a modified Ostwald viscosimeter according to the method of reference 10. Viscosities for most of the fuels were determined at -40° F and viscosities for several fuels showing desirable ignition characteristics were also determined at 77° F and at temperatures between -103° and -113° F.

Measurement of Ignition Delay

Apparatus and method. - Except for improvements in instrumentation, the apparatus, which is shown in figure 1, is the same as that described in reference 2. The function of the apparatus was to bring the fuel and oxidant into contact with each other at a desired initial temperature and to measure the time interval between the start of mutual contact and the first appearance of flame. This time interval was defined as the ignition-delay interval. One milliliter of the fuel was contained in a small pyrex glass ampule submerged in 3 milliliters of the acid oxidant in a 1- by 8-inch pyrex ignition-type test tube. Both the fuel and oxidant were cooled to a desired temperature by submersing the test tube in a constant-temperature bath contained in a clear-glass Dewar cylinder. The fuel ampule was broken by a stainless-steel rod that was struck by a falling weight. High-speed motion pictures (reference 2) show that the ampule is broken and the fuel and oxidant contact each other within an interval of less than 2 milliseconds. The extent of mixing probably varies somewhat as a result of individual

differences in ampules and viscosities of propellants. The insulated weight closed an electric circuit which provided a starting signal for the timing instruments at the moment the ampule was broken.

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Two types of instrument actuated by light emission were used simultaneously to measure the delay interval. Instantaneous indications were obtained from an electronic timer started through a thyratron relay circuit triggered by the starting signal and stopped by an amplified signal caused by light from the test tube striking a photocell. Continuous records of light emission against time were also obtained by means of a camera oscillograph. The recorded signal was a 2000-cycle-per-second carrier wave modulated by the output of a photocell. The start of the ignition-delay interval on the oscillograph record was indicated by a signal from an argon bulb near the photocell which was shorted out by a thyratron when the falling weight made electric contact with the rod. Another channel on the oscillograph was used to record the amplified output of a microphone which was about 1 foot from the apparatus; an indication of pressure fluctuations during the reaction of the propellants was thus obtained simultaneously with the light emission record.

Unless otherwise noted, the ignition data reported herein were obtained from the oscillograph records. The electronic counter was used to monitor and check the results, and the microphone record also served as an auxiliary indication of the start of the ignition-delay interval and a secondary check on the start of ignition.

Interpretation of records. - Illustrative examples of the oscillograph records from a series of experiments giving good reproducibility and a series giving wide variations are shown in figures 2 and 3, respectively. In figures 2(a) and 2(b) are shown light-emission and sound records, respectively, from four experiments with 30 percent aniline plus 70 percent triethylamine and a red fuming nitric acid at -76° F. The vertical bars are timing marks, 10 milliseconds apart. The light-emission-record number 1 (fig. 2(a)), for example, is interpreted as follows: The width of the carrier signal represents the intensity of light striking the photocell. The start of the ignition-delay interval is indicated at A by the sharp decay of the signal due to the extinguishing of the argon pilot light by the weight striking the rod. At B (25 milliseconds) the first of several short rapid flashes occurred but continuous flame did not start until C (37 milliseconds). In the intervals D to E and F to G the photocell was saturated with strong light. The saturated intervals are identified by the carrier signal being less than the ground level as in the interval between A and B. The records of experiments 2 and 4 were obtained with a different photoelectric pickup than those of experiments 1 and 3 and the quality of the signal was less satisfactory. The irregular

fluctuations during the first parts of records from experiments 2 and 4 (fig. 2(a)) were attributed to microphonic pickup and were not defined as flashes. Flashes were indicated by very sharp short disturbances of the signal.

The sound records obtained simultaneously are shown in figure 2(b). The validity of the start signal A of experiment 1 (fig. 2(a)) is confirmed by the sound record (experiment 1, fig. 2(b)), which starts to become fuzzy (indicating noise) at the same instant A within an interval of the order of 1 millisecond. At C (fig. 2(b)), 37 milliseconds from the start of the noise, a strong pressure pulse is indicated by a dip in the sound record and corresponds to the start of the continuous interval of light emission (fig. 2(a)). The remainder of the sound record is difficult to interpret because signals from vibrations of the flame are probably mixed with those from mechanical vibrations of the hood in which the experiments were conducted. The ignition-delay intervals as determined by the electronic timer, the times of short flashes and the starts of continuous flames as indicated by the light-emission records (fig. 2(a)), and the first strong pressure pulse from sound records (fig. 2(b)) are shown in the following table:

Experiment	Ignition delay from electronic timer (milliseconds)	Time of short flashes (milliseconds)	Start of first continuous flame (milliseconds)	Start of first strong pressure pulse (milliseconds)
1	24	25	37	37
2	34	34 37	37	34
3	38	38	38	36
4	35	35 38	38	38

The ignition-delay intervals as determined by the electronic counter varied from 24 to 38 milliseconds, because the counter was stopped during experiments 1, 2, and 4 by short flashes of light, instead of by the start of continuous flame. The starts of the continuous flames were in close agreement, varying between 37 and 38 milliseconds, and these data were accepted as the ignition-delay intervals.

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Figure 3 shows oscillograph records for 30 percent xylidine plus 70 percent triethylamine with red fuming nitric acid at -87° F, and represents a series of records which were more difficult to interpret than those in figure 2. The light-emission record of experiment 1 shows short rapid flashes starting at B (114 milliseconds) and start of continuous flame at C (128 milliseconds). The record of experiment 2, however, shows only a momentary weak flame at C and the gradual start of continuous flame at D (175 milliseconds). The record of experiment 3 shows D to be the start of a series of weak flames with stronger flames occurring at E (330 milliseconds) and F (390 milliseconds). In record 3, D was accepted as the start of ignition because it indicates the start of a series of weak flames corresponding to the first strong continuous flame on record 2. Figure 3 also shows unusually large deviations between the light-emission records and the sound records; the sound records were disregarded. Although occasionally, as in experiments 2 and 3 (fig. 3), selection of the ignition-delay interval was somewhat arbitrary, the numerical data in such instances nevertheless indicate trends.

The data of figure 3 also illustrate the fact that ignition in some cases appears to be a periodic process. Variations in data may thus be a function of the fuel and oxidant used and the extent of mixing. The periodic process possibly may be affected also by surface conditions and trace impurities.

RESULTS AND DISCUSSION

Fluid Properties of Fuels and Oxidants at Low Temperatures

The use of a liquid rocket propellant at low temperature may be limited by either freezing or excessive viscosity.

Freezing temperature of acid oxidants. - Freezing, rather than viscosity, limits the fluidity of acid oxidants at low temperatures. Approximate freezing temperatures of most of the acids used in this investigation are presented in table I. Acids investigated which had freezing temperatures lower than -76° F were a mixed acid containing 29 percent sulfuric acid (MA-0-29), red fuming nitric acids containing approximately 3 percent water and 16 and 19 percent nitrogen tetroxide (RFNA-3-16 and RFNA-3-19), a white fuming nitric acid containing 9 percent water (WFNA-9), and nitric acids containing 8 percent or more water and potassium nitrate or perchloric acid [WFNA-8(6-KNO_3), WFNA-9(7-$HClO_4$), WFNA-11(4-$HClO_4$)]. The acids also showed tendencies to supercool, and it was possible to obtain ignition-delay data with RFNA-3-19 at temperatures as low as -105° F. The tendency for these acids to supercool may constitute an emergency safety factor of practical importance.

Viscosities of fuels. - Kinematic-viscosity - temperature data within the range from 77° to -113° F for several aromatic amines, triethylamine, and blends of aromatic amines with triethylamine are presented in figure 4. The kinematic-viscosity and temperature scales are similar to those recommended by the A.S.T.M. for use with petroleum products. The data for each of the amine fuels are shown to fall close to a straight line, thereby following the relation (reference 11)

$$\log \log (\nu + c) = A \log T + B$$

where

ν kinematic viscosity, centistokes

T absolute temperature, °R

c constant, ~ 0.6 to 0.75

A,B constants, functions of fuel

The blends of secondary and tertiary aromatic amines were more fluid (less viscous) at low temperatures than the corresponding blends of primary amines. Eight blends are shown in figure 4 to have kinematic viscosities less than 10 centistokes at -40° F and less than 500 centistokes at -105° F.

The blends, apparently, are nonideal solutions. If the solutions were ideal, the kinematic viscosity for a blend could be calculated as

$$\nu = \frac{1}{(\rho_A V_A + \rho_B V_B)\left(\frac{X_A}{\rho_A \nu_A} + \frac{X_B}{\rho_B \nu_B}\right)}$$

where

ν, ν_A, ν_B kinematic viscosities of blend, component A, and component B, respectively, centistokes

ρ_A, ρ_B densities of components A and B, respectively

X_A, X_B mole fractions A and B, respectively

V_A, V_B volume fractions A and B, respectively

For several blends, calculated and observed kinematic viscosities are shown in the following table:

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Aromatic amine	Percent aromatic amine in triethylamine		Viscosity (centistokes)					
			70° F			-40° F		
	Volume	Mole	Calculated	Observed	Ratio, observed / calculated	Calculated	Observed	Ratio, observed / calculated
Aniline	50	60	0.96	1.72	1.8	----	----	---
	30	40	.72	1.07	1.5	----	----	---
o-Toluidine	50	56	.90	1.57	1.7	----	----	---
	30	36	.69	1.01	1.5	----	----	---
N-Ethylaniline	50	53	.79	1.08	1.4	2.03	7.40	3.7
	30	32	.64	.81	1.3	1.52	3.40	2.2
N,N-Diethylaniline	50	47	.74	.98	1.3	1.84	3.75	2.0
	30	27	.62	.74	1.2	1.43	2.18	1.5
N,N-Diallylaniline	50	44	.72	1.08	1.5	1.74	4.92	2.8

The observed viscosities are higher than those calculated, especially at low temperature, thereby indicating probable presence of complexes between the components of the blends (reference 12).

Ignition Study of Acid Oxidants at -40° F

Early in the investigation a 50 percent by volume blend of xylidines in triethylamine (suggested by reference 13) was found to be fairly fluid at -40° F and ignited reproducibly with concentrated white fuming and anhydrous nitric acids. This blend was therefore selected as a reference fuel to study the comparative ignitibility at -40° F of several acids. Some of the acids were also investigated with a 50 percent by volume blend of N,N-diallylaniline in triethylamine, inasmuch as reference 14 shows N,N-diallylaniline to have desirable ignition characteristics. The results of this investigation of acid oxidants are shown in table II.

Acids giving short ignition delays. - As shown in the following table, a mixed acid, several red fuming nitric acids, and white fuming nitric acids containing 2 percent or less water gave short average ignition-delay intervals at -40° F with the two fuels:

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Acid	Approximate freezing temperature of acid (°F)	Average ignition-delay interval at -40° F (milliseconds)	
		50 percent xylidine in triethylamine	50 percent N,N-diallylaniline in triethylamine
MA-2-17	-68	28	27
RFNA-3-16	-82	31	28
RFNA-3-19 (lot a)	-87	31	26
RFNA-3-29	-68	31	--
RFNA-5-35	---	34	51
NA(anh)-0-3	-45	34	17
WFNA-2	-45	42	20

Effect of water in white fuming nitric acid. - With white fuming nitric acids the average ignition delays of the two fuels increased with increase of water in acid as shown by the following table:

Acid	Water in acid (percent by weight)	Average ignition-delay interval at -40° F (milliseconds)	
		50 percent xylidine in triethylamine	50 percent N,N-diallylaniline in triethylamine
NA(anh)-0-3	0.3	34	17
WFNA-2	1.8	42	20
WFNA-7	6.8	114	No ignition
WFNA-9	8.7	No ignition	----------

Other acids containing 8 percent or more water, WFNA-8(6-KNO_3), WFNA-9(7-$HClO_4$), and WFNA-11(4-$HClO_4$), did not ignite. Similar trends were observed with NA(anh)-0-3, WFNA-2, WFNA-7, and WFNA-11(4-$HClO_4$) in a 50-pound-thrust rocket chamber (reference 15).

Effect of ammonium nitrate in white fuming nitric acid. - The acids WFNA-2(5-NH_4NO_3) and WFNA-2(10-NH_4NO_3), prepared by addition of 5 and 10 percent ammonium nitrate to WFNA-2, were found to ignite 50 percent xylidine in triethylamine with average delays of two to three times those obtained with WFNA-2 alone.

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Ignition by low-freezing acids. - A comparison of average ignition-delay intervals at -40° F for several acids freezing below -76° F (-60° C) is shown in the following table:

Acid	Approximate freezing temperature of acid (°F)	Average ignition-delay interval at -40° F (milliseconds)	
		50 percent xylidine in triethylamine	50 percent N,N-diallylaniline in triethylamine
RFNA-3-19 (lot a)	-87	31	26
RFNA-3-16	-82	31	28
MA-0-29	-87	48	67
WFNA-9	-81	No ignition	--
WFNA-8(6-KNO_3)	-96	No ignition	--
WFNA-9(7-$HClO_4$)	-78	No ignition	--
WFNA-11(4-$HClO_4$)	-91	No ignition	--

Because of low freezing temperature and short average ignition delays, acids of the type RFNA-3-19 were used for further ignition experiments at several temperatures.

Ignition Study of Fuels at -40° F

A study was made at -40° F to determine the ignitibility of several fuels with representative acids having vigorous and mild ignition characteristics, respectively. The fuels were first investigated with (a) mixed acid, inasmuch as references 1 to 3 show that mixed acid has desirable low-temperature ignition characteristics, and (b) white fuming nitric acid to show their ignitibility with a less vigorous igniting acid. The acids MA-3-17 and WFNA-7 were used for most of these experiments.

Several of these fuels were also investigated with two acids found to have low freezing temperatures (table I); namely, (a) RFNA-3-19, freezing at -87° F and showing desirable ignition characteristics, and (b) WFNA-9, freezing at -81° F. In preliminary experiments (table II) WFNA-9 was unsatisfactory as an igniting acid, but it may be a desirable propellant on the basis of handling and is representative of white fuming acids with freezing temperatures depressed by addition of water.

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Ignitibility of blends of aromatic amines in triethylamine. - As shown in table III, with the mixed acid MA-2-17 blends of the aromatic amines, aniline, N-ethylaniline, N,N-diethylaniline, N,N-diallylaniline, o-toluidine, and xylidines, respectively, in triethylamine ignited at -40° F with most of the average delays between 28 and 48 milliseconds and no average greater than 65 milliseconds. With the white fuming nitric acid containing 7 percent water (WFNA-7), all the investigated blends of aromatic amines in triethylamine (except 50 percent N-ethylaniline and 50 percent N,N-diallylaniline, respectively) ignited at -40° F with average delays ranging from 23 to 115 milliseconds.

Ignition of blends of aromatic amines in triethylamine by low-freezing acids. - The investigation with low-freezing red fuming nitric acids (RFNA-3-19) and low-freezing white fuming nitric acid (WFNA-9) at -40° F (table III) showed that the blends of aromatic amines in triethylamine ignited much more satisfactorily with the red fuming acid; the average delays with RFNA-3-19 were between 20 and 55 milliseconds, but with WFNA-9 most of the ignitions were sporadic or did not occur and the average delays were all greater than 100 milliseconds. In these experiments blends of 50 percent aniline and 30 percent xylidines, respectively, in triethylamine showed the most consistent ignitibility with WFNA-7 and WFNA-9.

Effect of blending aromatic amines with triethylamine. - Not only are blends of aromatic amines with triethylamine more fluid at low temperatures than the aromatic amines alone (fig. 4), but in the case of N-ethylaniline and N,N-diethylaniline the blends tended to show more desirable ignition characteristics than either of the parent substances, as shown in the following table:

Fuel (percent by volume in triethylamine)	Average ignition-delay interval at -40° F (milliseconds)		
	MA-2-17	RFNA-3-19	WFNA-7
N-ethylaniline	51	No ignition	No ignition
50 N-ethylaniline	45	54	Sporadic
30 N-ethylaniline	48	36	105
Triethylamine	No ignition	755	Sporadic
N,N-diethylaniline	90	No ignition	No ignition
50 N,N-diethylaniline	35	42	33
30 N,N-diethylaniline	65	33	94
Triethylamine	No ignition	755	Sporadic

Because of freezing temperatures higher than -40° F, the ignition delays of pure primary aromatic amines were not determined in this investigation, but trends may be noted in a comparison of ignition delays at -40° F of several 30 and 50 percent blends of aromatic amines in triethylamine, as shown in the following table:

Aromatic amine	Aromatic amine in triethyl-amine (percent by volume)	Average ignition-delay interval at -40° F (milliseconds)			
		MA-2-17	RFNA-3-19	WFNA-7	WFNA-9
Aniline	50	33	27	44	102
	30	38	21	23	380
N-ethylaniline	50	45	54	Sporadic	Sporadic
	30	48	36	105	Sporadic
N,N-diethylaniline	50	35	42	33	Sporadic
	30	65	33	94	Sporadic
o-Toluidine	50	36	27	42	Sporadic
	30	36	24	102	Sporadic
Xylidines	50	32	31	114	No ignition
	30	42	31	78	119

These data show that at -40° F with mixed acid MA-2-17 the 50 percent blends of aromatic amines in triethylamine gave shorter average ignition delays, but with low-freezing red fuming nitric acid RFNA-3-19 the more fluid 30 percent blends gave shorter delays. No significant trend, however, was found with acids WFNA-7 and WFNA-9.

Fuels causing explosions. - Three other fuels showed short ignition delays at -40° F with nitric acids containing 2 percent or less water, but because they damaged the equipment with vigorous explosions, no further investigation was undertaken with this apparatus. These fuels were blends of 70 percent furfuryl alcohol plus 30 percent aniline (poor fluid characteristics), 56 percent furfuryl alcohol plus 24 percent aniline plus 20 percent methanol, and α-furfuryl mercaptan. The α-furfuryl mercaptan has shown satisfactory ignition with NA(anh)-0-3 and WFNA-2 at -40° F in a 50-pound-thrust rocket chamber (reference 15).

Ignitibility of Blends of Aromatic Amines in Triethylamine with Red Fuming Nitric Acid Within Temperature Range 70° to -105° F

Ignition-delay characteristics of several blends of aromatic amines in triethylamine (table III) having viscosities less than 10 centistokes at -40° F were investigated with low-freezing red fuming nitric acid (RFNA-3-19) at several temperatures from 70° to -105° F and these data are shown in table IV. The reference fuel, a 50 percent blend of xylidines in triethylamine, was also investigated at several temperatures.

Effect of blending. - At several temperatures with RFNA-3-19 the 30 percent blends of several aromatic amines in triethylamine tended to give shorter ignition-delay intervals than the 50 percent blends, as shown in the following table:

Aromatic amine	Aromatic amine in triethylamine (percent by volume)	Average ignition-delay interval (milliseconds)			
		70° F	-40° F	-76° F	-105° F
Xylidines	50	27	31	56	----------
	30	19	31	49	No ignition
N-ethylaniline	50	35	54	74	875
	30	26	36	61	664
N,N-diethylaniline	50	36	42	70	No ignition
	30	24	33	160	No ignition

As has been previously noted, the same trend was shown for blends of other aromatic amines in triethylamine with RFNA-3-19 at -40° F. The better ignitibility of the 30 percent blends is a practical advantage because these mixtures also have lower viscosities than the corresponding 50 percent blends (fig. 4).

Comparison of 30 percent blends of primary and secondary aromatic amines in triethylamine. - Because of the lower viscosities of the 30 percent blends, more of these blends were investigated. A comparison of the ignition delays of several 30 percent aromatic blends in triethylamine with RFNA-3-19 at several temperatures indicates that the 30 percent primary amine blends tend to ignite more readily than the 30 percent secondary and tertiary amine blends, as shown in the following table:

Aromatic amine, 30 percent by volume in triethylamine	Average ignition delay with RFNA-3-19 (milliseconds)				
	70° F	-40° F	-76° F	-87° F	-105° F
Primary					
o-Toluidine	19	24	38	61	210
Aniline	21	21	37	108	>1000
Xylidines	19	31	49	148	No ignition
Secondary and tertiary					
N-ethylaniline	26	36	61	---	664
N,N-diethylaniline	24	33	160	---	No ignition

Of the fuels investigated, the blend of 30 percent o-toluidine in triethylamine appeared to have the most desirable ignition characteristics at low temperatures. (The data obtained at -105° F were with supercooled acid.)

Sensitivity of a blend of N,N-diallylaniline in triethylamine to temperature and water in acid. - The ignition of a blend of 50 percent N,N-diallylaniline plus 50 percent triethylamine appeared to be variable and sensitive to temperatures (table IV) as well as to water content of acid (table II). Temperature sensitivity of this blend, however, was less pronounced when its ignition was investigated with red fuming nitric acid containing 3.5 percent water and 16.0 percent nitrogen tetroxide in a 50-pound-thrust rocket chamber (reference 15), wherein it was found to ignite satisfactorily from 110° to -95° F.

Blends of Aromatic Amines plus α-Furfuryl Mercaptan

Experiments with blends of aromatic amines plus α-furfuryl mercaptan (table IV) were discontinued because of inconsistent results probably caused by chemical changes which were noticeable after the mixtures stood several days.

SUMMARY OF RESULTS

An investigation was made of the fluid properties and ignition-delay characteristics of approximately 90 fuel-oxidant combinations at -40° F and some of these combinations were investigated at several other temperatures within the range 70° to -105° F; the following results were obtained:

1. Several acids were determined to have freezing temperatures less than -76° F. Of these acids, the red fuming nitric acids containing approximately 3 percent water and 16 and 19 percent nitrogen tetroxide gave satisfactory ignition with several fuels at -40° F.

2. Kinematic viscosities of aromatic amines were reduced by blending 50 and 30 percent by volume aromatic amine in triethylamine. Eight such blends had kinematic viscosities less than 10 centistokes at -40° F and less than 500 centistokes at -105° F. The blends were apparently nonideal solutions.

3. At -40° F, 11 blends of 30 and 50 percent aromatic amines, respectively, in triethylamine were found to give generally satisfactory ignition with mixed acid containing 2 percent water and 17 percent sulfuric acid and low-freezing red fuming nitric acid containing 3 percent water and 19 percent nitrogen tetroxide (average ignition-delay intervals from 20 to 65 milliseconds). All but two of these blends ignited with white fuming nitric acid containing 7 percent water with average delays varying from 23 to 115 milliseconds, but generally sporadic ignition was obtained with low-freezing white fuming nitric acid containing 9 percent water.

4. With mixed acid, red fuming nitric acid, and white fuming nitric acid at -40° F, blends of 50 and 30 percent by volume of N-ethylaniline and N,N-diethylaniline, respectively, in triethylamine gave shorter average ignition delays than the unblended parent components.

5. Comparisons of blends, respectively, of 50 and 30 percent by volume aromatic amines in triethylamine showed that the 50 percent blends gave shorter ignition-delay intervals with mixed acid (2 percent water and 17 percent sulfuric acid) at -40° F, but with red fuming nitric acid (approximately 3 percent water and 19 percent nitrogen tetroxide) the more fluid 30 percent blends gave shorter delay intervals at temperatures of 70°, -40°, and -76° F.

6. Low-freezing red fuming nitric acid (approximately 3 percent water and 19 percent nitrogen tetroxide) gave the following average ignition delays with 30 percent by volume blends of aromatic amines in triethylamine (the acid had an approximate freezing temperature of -87° F and was supercooled at -105° F).

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Aromatic amine, 30 percent by volume in triethylamine	Average ignition delay (milliseconds)				
	70° F	-40° F	-76° F	-87° F	-105° F
Primary					
o-Toluidine	19	24	38	61	210
Aniline	21	21	37	108	>1000
Xylidines	19	31	49	148	No ignition
Secondary and tertiary					
N-ethylaniline	26	36	61	---	664
N,N-diethylaniline	24	33	160	---	No ignition

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

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TABLE I - DESCRIPTION OF ACIDS USED IN IGNITION EXPERIMENTS

Code designation	Approximate freezing temperature (°F)	Composition (percent by weight)					Remarks
		Nitric acid HNO_3	Sulfuric acid H_2SO_4	Nitrogen tetroxide N_2O_4	Water, H_2O (by difference)	Other	
Mixed acids							
MA-5-15	----	80.0	15.3	----	4.7		Prepared from chemically pure white fuming nitric acid and oleum (reference 2).
MA-2-17	-68	81.3	17.1	----	1.6		Prepared from commercial white fuming nitric acid (received from manufacturer in glass bottles) and chemically pure oleum.
MA-4-17	----	79.4	16.7	----	3.9		A commercial mixed acid supplied by Bureau of Aeronautics, Department of the Navy (reference 2).
MA-0-29	-87[a]	71.0	29.0	----	----		Prepared from commercial white fuming nitric acid (aluminum drum) and chemically pure oleum. Composition calculated.
Red fuming nitric acids							
RFNA-3-16	-82	80.8	----	15.8	3.4		Prepared by mixing commercial white fuming nitric acid (aluminum drum) and chemically pure red fuming nitric acid.
RFNA-3-19(lot a)	-87	78.0	----	19.0	3.0		Prepared by mixing commercial anhydrous nitric acid (aluminum drum) and chemically pure red fuming nitric acid.
(lot b)	-87	78.5	----	18.8	2.7		Prepared in same manner as lot a.
(lot c)	-87	78.8	----	19.0	2.2		Prepared by slow addition of water to chemically pure anhydrous red fuming nitric acid at low temperature.
RFNA-3-29	-68	67.6	----	29.2	3.2		A chemically pure red fuming nitric acid.
RFNA-5-35	----	60.1	----	34.7	5.2		A chemically pure red fuming nitric acid.
White fuming nitric acids							
NA(anh)-0-3	-45	97.1	----	2.6	0.3		A commercial acid supplied in an aluminum drum, but stored in pyrex glass shortly after receipt.
WFNA-2	-45	97.7	----	0.5	1.8		A commercial acid supplied and stored in an aluminum drum.
WFNA-7	-69	93.0	----	0.2	6.8		A chemically pure acid stored about 2 years in soft glass bottles.
WFNA-9	-81	91.1	----	0.2	8.7		Prepared by slow addition of water to WFNA-7 at -40° F. Composition calculated.
Acids containing nitrate salts							
WFNA-2(5-NH_4NO_3)	-54	92.8	----	0.5	1.7	5.0 ammonium nitrate	Prepared by dissolving ammonium nitrate in WFNA-2. Composition calculated.
WFNA-2(10-NH_4NO_3)	-23[b]	87.9	----	0.5	1.6	10.0 ammonium nitrate	Prepared as above. Composition calculated.
WFNA-8(6-KNO_3)	-96	85.9	----	0.4	7.7	6.0 potassium nitrate	Prepared by addition of potassium nitrate and water to commercial white fuming nitric acid. Composition calculated.
Acids containing perchloric acid							
WFNA-9(7-$HClO_4$)	-78	83.9	----	0.4[c]	9.0	6.7 perchloric acid	Prepared by addition of 70 percent perchloric acid and water to commercial white fuming nitric acid. Composition calculated.
WFNA-11(4-$HClO_4$)	-91	85.0	----	0.4[c]	10.5	4.1 perchloric acid	Prepared as above. Composition calculated.

[a]Data of reference 16.
[b]Greater portion of solids melted as temperature increased to -61° F.
[c]Colorless solution indicates nitrogen tetroxide - nitrogen dioxide not present in free state.

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TABLE II - IGNITION STUDY AT -40° F OF SEVERAL NITRIC ACID OXIDANTS WITH TWO 50-50 (BY VOLUME) BLENDS OF AROMATIC AMINE PLUS TRIETHYLAMINE

[DAA, N,N-diallylaniline; T_f, approximate freezing temperature, °F.]

Acid oxidant (composition, percent by weight)	Fuel in triethylamine (50 percent by volume)	Number of trials	Ignition-delay interval at -40° F (milliseconds) [Data point represents average]
Mixed acids			
MA-2-17 (T_f, -68° F) 81.3 HNO_3-17.1 H_2SO_4-1.6 H_2O	Xylidines DAA	3 4	
MA-0-29 (T_f, -87° F)[a] 70.7 HNO_3-29.3 H_2SO_4[b]	Xylidines DAA	4 3	
Red fuming nitric acids			
RFNA-3-16 (T_f, -82° F) 80.8 HNO_3-15.8 N_2O_4-3.4 H_2O	Xylidines DAA	4 4	
RFNA-3-19 (lot a)(T_f, -87° F) 78.0 HNO_3-19.0 N_2O_4-3.0 H_2O	Xylidines DAA	5 4	
RFNA-3-29 (T_f, -68° F) 67.6 HNO_3-29.2 N_2O_4-3.2 H_2O	Xylidines	3	
RFNA-5-35 60.1 HNO_3-34.7 N_2O_4-5.2 H_2O	Xylidines DAA	4 4	

10 20 40 60 100 200 400 600 1000

			10	20	40	60	100	200	400	600	1000
White fuming nitric acids											
NA(anh)-0-3 (T_f, -45° F) 97.1 HNO_3-2.6 N_2O_4-0.3 H_2O	Xylidines DAA	10 4			○						
				○							
WFNA-2 (T_f, -45° F) 97.7 HNO_3-0.5 N_2O_4-1.8 H_2O	Xylidines[c] DAA	6 6		←—○	○						
WFNA-7 (T_f, -69° F) 93.0 HNO_3-0.2 N_2O_4-6.8 H_2O	Xylidines DAA	8 2					○ (Weak)		No ignition →		
WFNA-9 (T_f, -81° F) 91.1 HNO_3-0.2 N_2O_4-8.7 H_2O[b]	Xylidines	2							No ignition →		
Special acids											
WFNA-2(5-NH_4NO_3) (T_f, -54° F) 92.8 HNO_3-5.0 NH_4NO_3 -0.5 N_2O_4-1.7 H_2O[b]	Xylidines	3				—○—					
WFNA-2(10-NH_4NO_3) (T_f, -23° F) 87.9 HNO_3-10.0 NH_4NO_3 -0.5 N_2O_4-1.6 H_2O[b]	Xylidines	4					—○—				
WFNA-8(6-KNO_3) (T_f, -96° F) 85.9 HNO_3-6.0 KNO_3 -7.7 H_2O-0.4 N_2O_4	Xylidines	2							No ignition →		
WFNA-9 (7-$HClO_4$) (T_f, -78° F) 83.9 HNO_3-6.7 $HClO_4$-9.0 H_2O[b]	Xylidines	2							No ignition →		
WFNA-11(4-$HClO_4$) (T_f, -91° F) 85.0 HNO_3-4.1 $HClO_4$-10.5 H_2O[b]	Xylidines	2							No ignition →		

[a]Data from reference 16.
[b]Calculated approximate composition.
[c]Ignition delays from electronic timer only.

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TABLE III - IGNITION STUDY AT -40° F OF VARIOUS FUELS WITH SEVERAL NITRIC ACID OXIDANTS

[Symbols for acid oxidants are designated in table I; ν, kinematic viscosity of fuel at -40° F, centistokes]

Fuel (percent by volume)	Acid oxidant	Number of trials	Ignition-delay interval at -40° F (milliseconds) [Data point represents average]
Aromatic and aliphatic amines			
50-aniline - 50-triethylamine (ν, 30.1)	MA-2-17	4	
	RFNA-3-19(lot c)	4	
	WFNA-7	4	
	WFNA-9	4	
30-Aniline - 70-Triethylamine (ν, 8.45)	MA-2-17	4	
	RFNA-3-19(lot a)	4	
	WFNA-7	4	
	WFNA-9	4	(Weak)
N-Ethylaniline (ν, 44)	MA-2-17	6[a]	
	RFNA-3-19(lot c)	2	No ignition
	WFNA-7	2	No ignition
50-N-Ethylaniline - 50-Triethylamine (ν, 7.39)	MA-2-17	4	
	RFNA-3-19(lot a)	4	(1 of 4 ignited)
	WFNA-7	4	(3 of 4 ignited)
	WFNA-9	4	
30-N-Ethylaniline - 70-Triethylamine (ν, 3.40)	MA-2-17	4	
	RFNA-3-19(lot a)	4	
	WFNA-7	4	(3 of 4 ignited)
	WFNA-9	4	
N,N-Diethylaniline (ν, 37.5)	MA-2-17	4	
	RFNA-3-19(lot a)	2	No ignition
	WFNA-7	2	No ignition
50-N,N-Diethylaniline - 50-Triethylamine (ν, 3.75)	MA-2-17	4	
	RFNA-3-19(lot c)	6	
	WFNA-7	4	(1 of 4 ignited)
	WFNA-9	4	
30-N,N-Diethylaniline - 70-Triethylamine (ν, 2.18)	MA-2-17	4	
	RFNA-3-19(lot c)	4	
	WFNA-7	4	(1 of 4 ignited)
	WFNA-9	4	
50-N,N-Diallylaniline - 50-Triethylamine (ν, 4.92)	MA-2-17	5	
	RFNA-3-19(lot a)	4	
	WFNA-7	2	No ignition
50-o-Toluidine - 50-Triethylamine (ν, 19.8)	MA-2-17	4	
	RFNA-3-19(lot c)	4	
	WFNA-7	4	(3 of 4 ignited)
	WFNA-9	4	
30-o-Toluidine - 70-Triethylamine (ν, 5.69)	MA-2-17	4	
	RFNA-3-19(lot a)	4	
	WFNA-7	4	(3 of 4 ignited)
	WFNA-9	4	

			10 20 40 60 100 200 400 600 1000
50-Xylidines - 50-Triethylamine (ν, 17.5)	MA-2-17	6	
	RFNA-3-19(lot b)	5	
	WFNA-7	8	(Weak)
	WFNA-9	2	No ignition
30-Xylidines - 70-Triethylamine (ν, 4.85)	MA-2-17	4	
	RFNA-3-19(lot a)	7	
	WFNA-7	4	(Weak)
	WFNA-9	4	(Weak)
Crude Monoethylaniline (ν, 90)	MA-2-17	8[a]	
	WFNA-7	2	No ignition
Triethylamine (ν, 1.13)	MA-2-17	2	No ignition
	RFNA-3-19(lot c)	2	
	WFNA-7	2	(1 of 2 ignited)
Diethylenetriamine	MA-2-17	4[a]	
	WFNA-7	2	No ignition
Miscellaneous fuels			
70-Furfuryl Alcohol - 30-Xylenes (ν, 51)	MA-5-15	7[a]	
	NA(anh)-0-3	7[a]	(7 of 8 ignited)
	WFNA-7	8[a]	
Tetrahydrofuran	MA-2-17	2[a]	(1 of 2 ignited)
	WFNA-7	2	No ignition
3-Mercapto-1-Propanol	MA-2-17	4[a]	No ignition
Mixed Butyl Mercaptans (ν, 1.3)	MA-4-17	8[a]	
	WFNA-2	10[a]	(5 of 10 ignited)
Allyl Glycidyl Ether (ν, 6.15)	MA-2-17	4[a]	(3 of 4 ignited)
2-Methylpentadienes (contained inhibitor) (ν, .94)	MA-2-17	4[a]	
	WFNA-7	2	No ignition
50-2-Methylpentadienes - 50-n-Heptane	MA-2-17	2	No ignition
2,2,4,6-Tetramethyldihydropyridine (ν, 26.7)	MA-2-17	4[a]	
	WFNA-7	4	No ignition
1-Vinylcyclohexene-3	MA-2-17	2	No ignition
	WFNA-2	2	No ignition
Gum Turpentine (ν, 8.8)	MA-5-15	3[a]	
	RFNA-3-19(lot c)	2	No ignition
	WFNA-2	4	No ignition
Hydrazine Hydrate	MA-5-15	4[b]	No ignition
	WFNA-2	4	No ignition

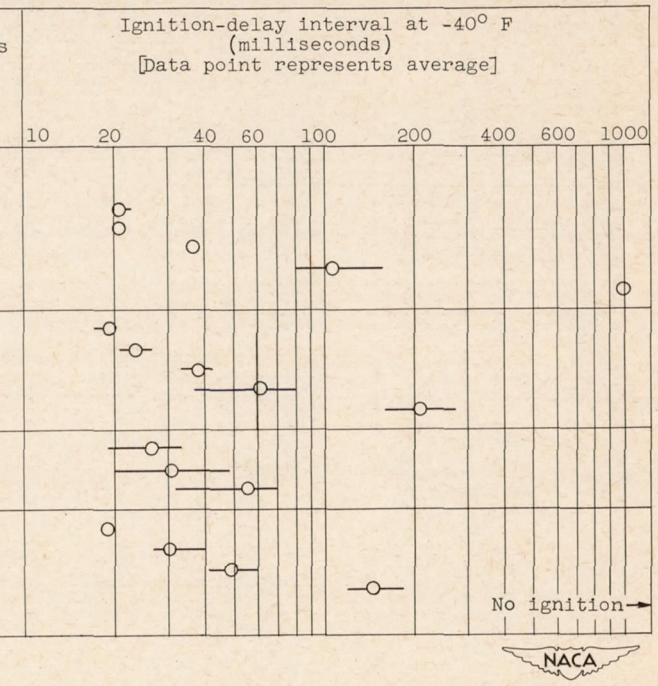
[a]Data from electronic timer.
[b]Temperature, -4° F.

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TABLE IV - STUDY AT SEVERAL TEMPERATURES OF VISCOSITIES AND IGNITION OF VARIOUS FUEL BLENDS WITH LOW-FREEZING RED FUMING NITRIC ACIDS CONTAINING APPROXIMATELY 3 PERCENT WATER AND 19 PERCENT NITROGEN TETROXIDE

[All ignition data are with RFNA-3-19(lot a) except as noted and all acids had freezing temperature of approximately -87° F and were supercooled at -105° F.]

Fuel (percent by volume)	Temperature (°F)	Fuel kinematic viscosity (centistokes) (fig. 4)	Number of trials	Ignition-delay interval at -40° F (milliseconds) [Data point represents average]
Primary aromatic amines in triethylamine				
30-Aniline	70	1.07	4[a]	
	-40	8.5	4	
	-76	45.0	4	
	-87	95.0	6	
	-105	480.0	2	
30-o-Toluidine	70	1.01	4[a]	
	-40	5.7	4	
	-76	19.5	4	
	-87	34.0	4	
	-105	110.0	4	
50-Xylidines	70	1.52	4[a]	
	-40	17.5	5	
	-76	138.0	6	
30-Xylidines	70	0.96	4[a]	
	-40	4.9	7[b]	
	-76	16.0	5	
	-87	27.0	6	
	-105	80.0	1	



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				10 20 40 60 100 200 400 600 1000
Secondary and tertiary aromatic amines in triethylamine				
50-N-Ethylaniline	70	1.08	4[a]	
	-40	7.4	4	
	-76	32.5	3	
	-87	63.0	--	
	-105	250.0	2	
30-N-Ethylaniline	70	0.81	4[a]	
	-40	3.4	4	
	-76	9.1	4	
	-87	14.0	--	
	-105	35.0	4	
50-N,N-Diethylaniline	70	0.98	4[a]	
	-40	3.8	6[a]	
	-76	9.3	4[a]	
	-87	13.0	--	
	-105	29.0	2	No ignition
30-N,N-Diethylaniline	70	0.74	4[a]	
	-40	2.18	4[a]	
	-76	4.2	4[a]	
	-87	5.4	--	
	-105	9.0	2	No ignition
50-N,N-Diallylaniline	70	1.08	4[a]	
	-40	4.9	4[b]	
	-76	14.0	10	
	-87	21.0	4	
	-105	52.0	1	No ignition
Aromatic amines in α-furfuryl mercaptan				
30-Xylidines	-76	------	1	(Brisant explosion)
	-105	------	1	No ignition
30-N,N-Diallylaniline	-40	------	4	(1 of 4 ignited)
	-76	------	10	(7 of 10 ignited)
	-87	------	6	
	-105	------	2	No ignition

[a]RFNA-3-19(lot c) used to determine ignition delays.
[b]RFNA-3-19(lot b) used to determine ignition delays.

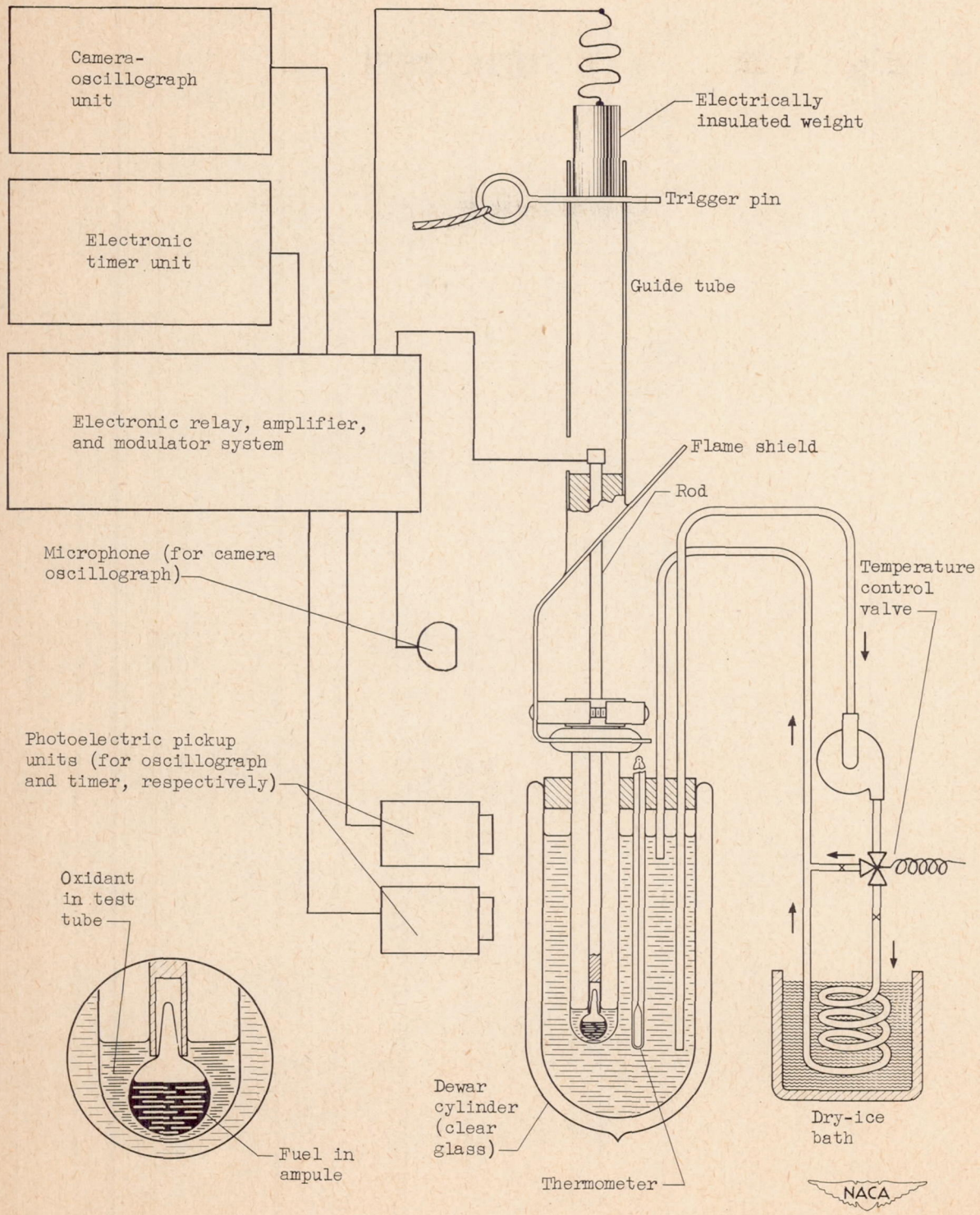
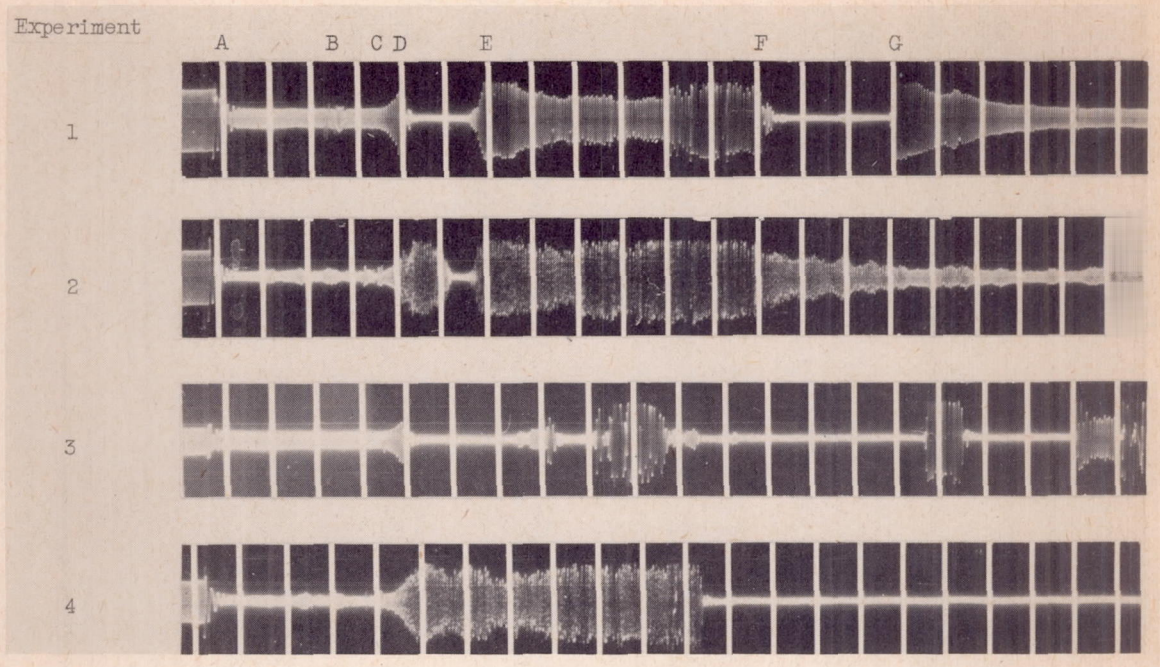
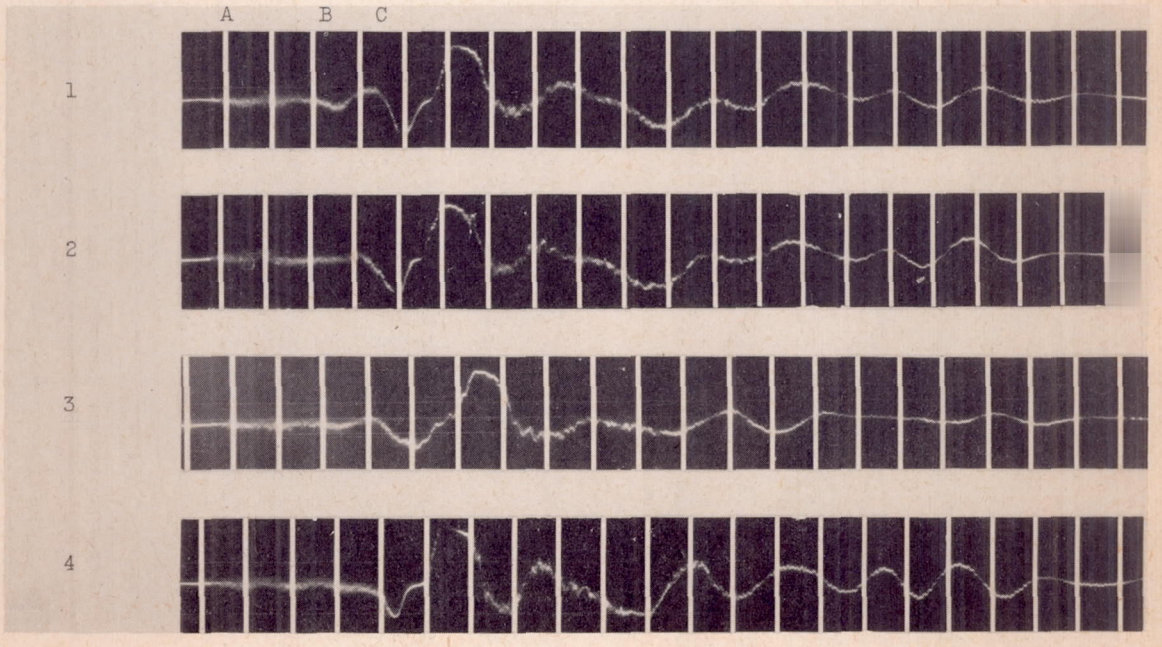


Figure 1. - Ignition-delay apparatus.



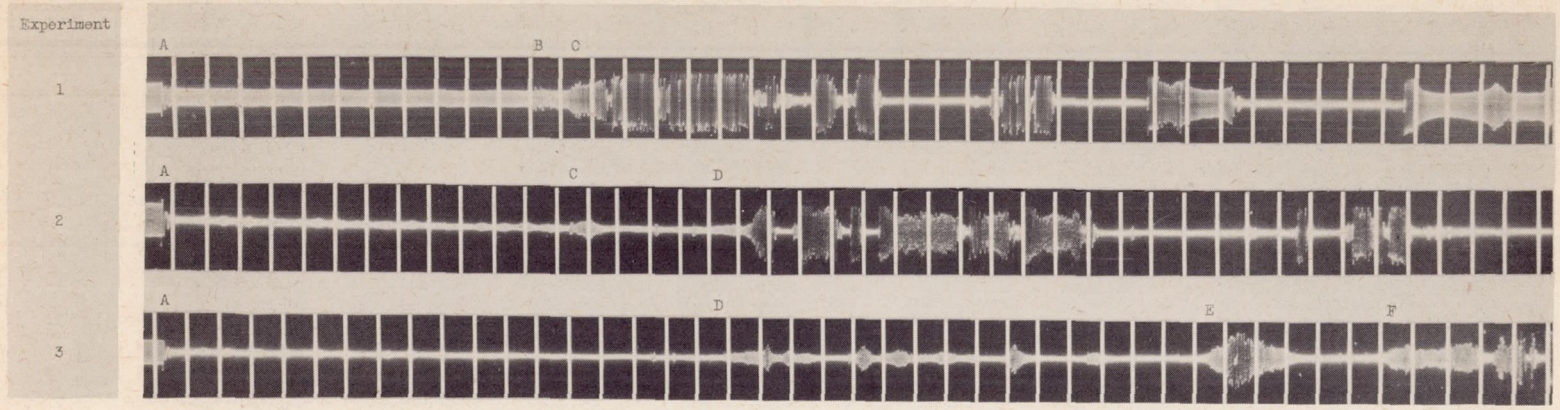
(a) Light-emission records.



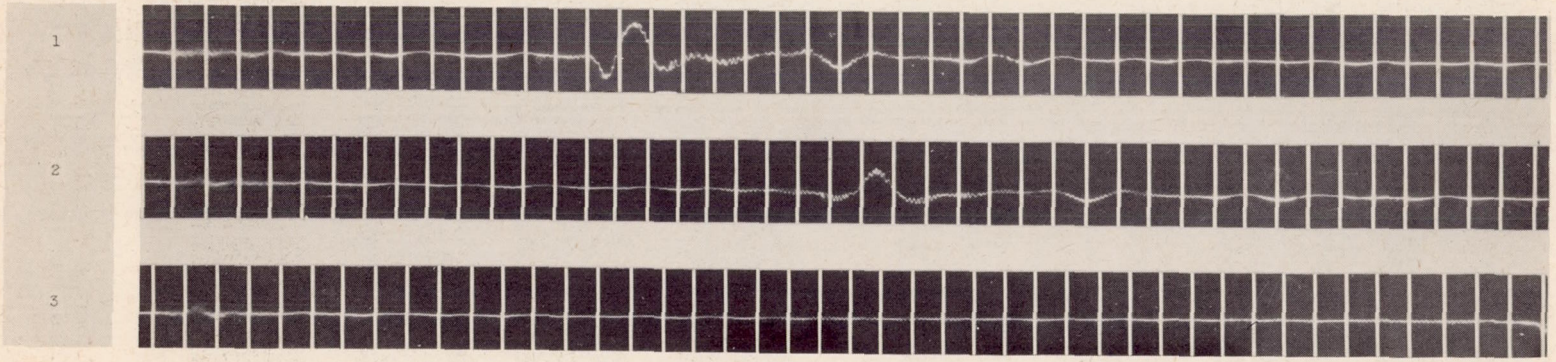
(b) Sound records.

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Figure 2. - Oscillograph records of light emission and sound from ignition of a blend of 30 percent aniline plus 70 percent triethylamine with RFNA-3-19 (lot a) at -76° F.



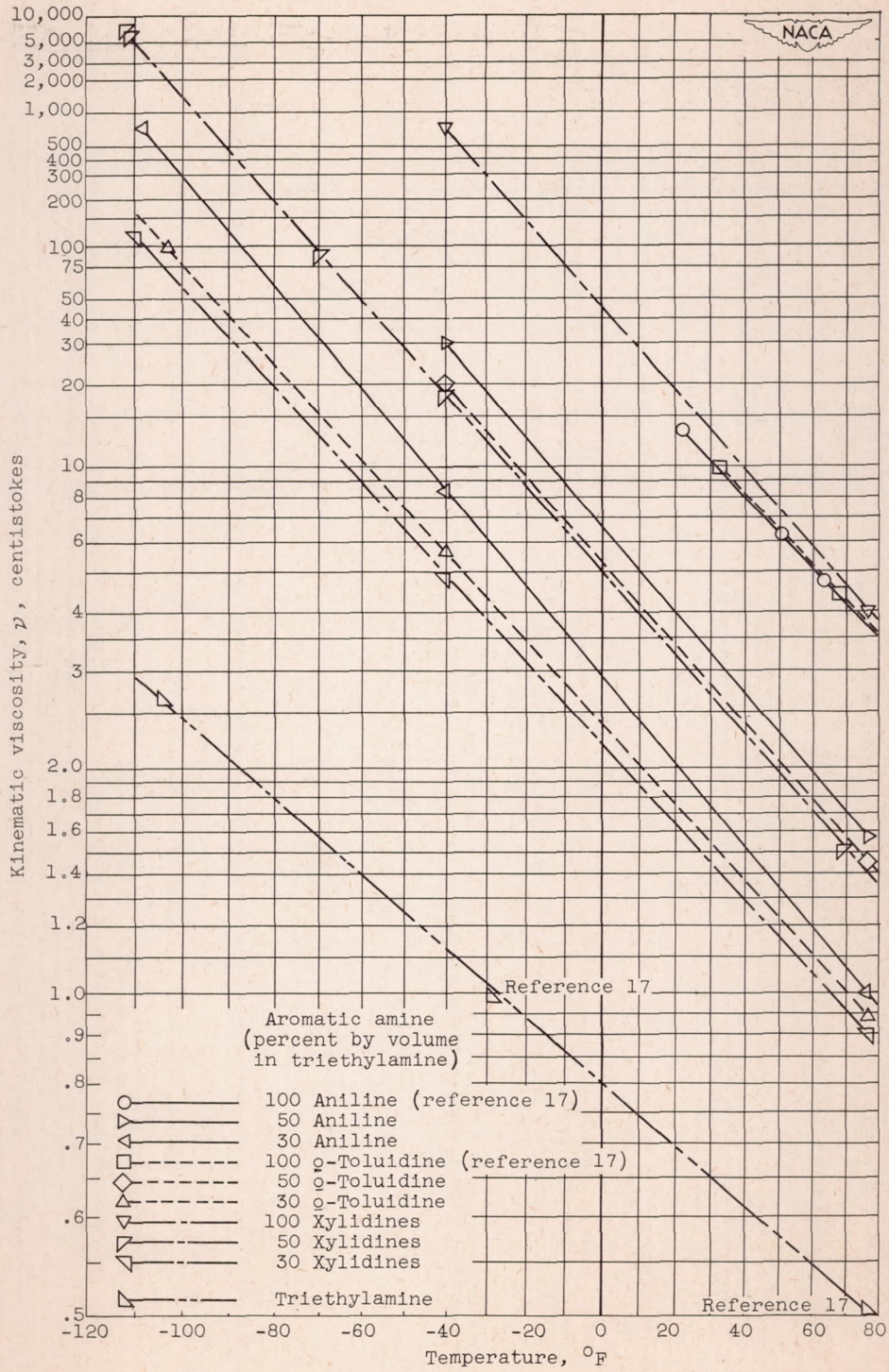
(a) Light-emission records.



(b) Sound records.

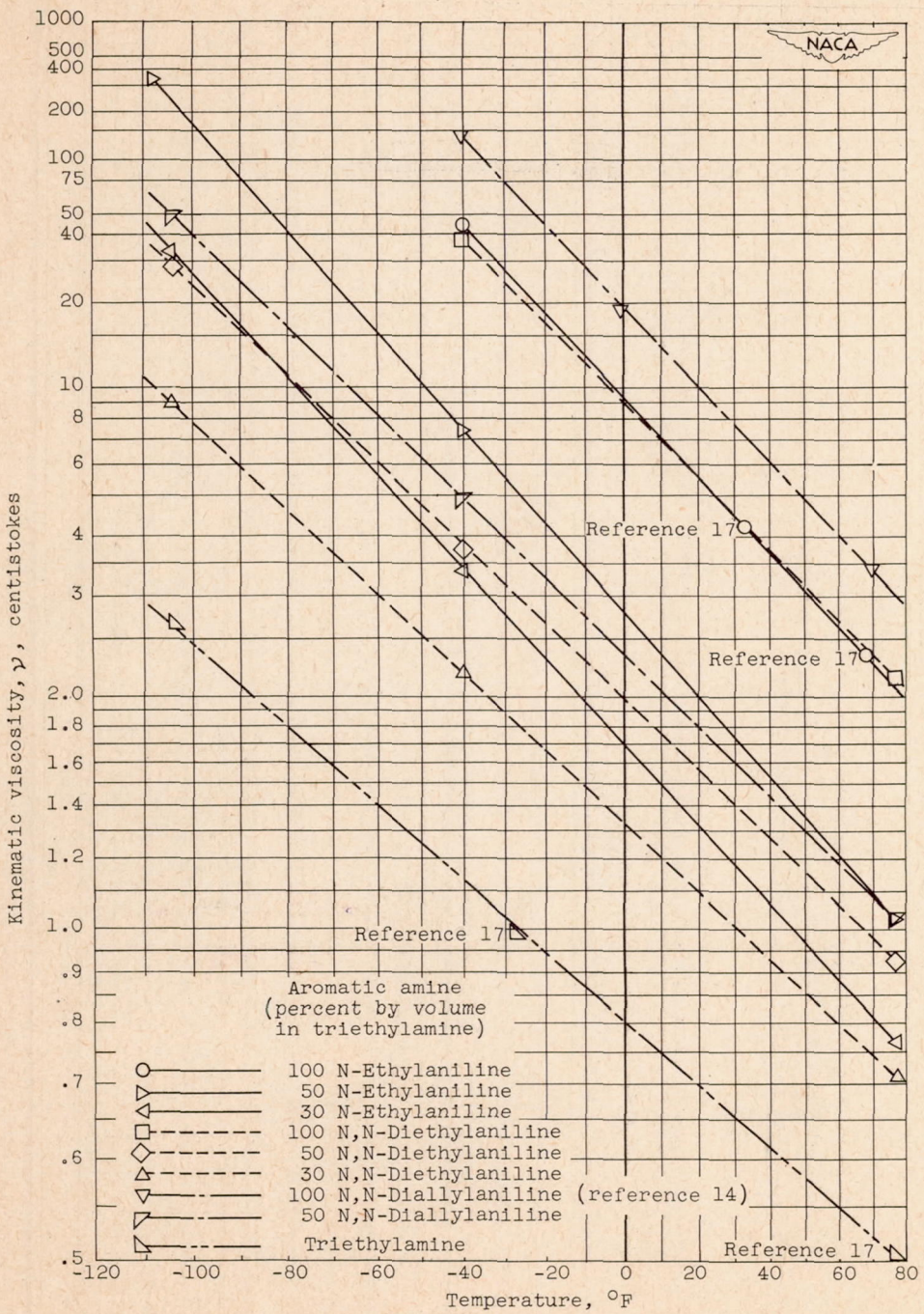
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Figure 3. - Oscillograph records of light emission and sound from ignition of a blend of 30 percent xylidine plus 70 percent triethylamine with RFNA-3-19 (lot a) at -87° F.



(a) Primary amines.

Figure 4. - Kinematic viscosities of aromatic amines, triethylamine, and blends of aromatic amines in triethylamine as functions of temperature. (Coordinate scales similar to those recommended by A.S.T.M.; see reference 11.)



(b) Secondary and tertiary amines.

Figure 4. - Concluded. Kinematic viscosities of aromatic amines, triethylamine, and blends of aromatic amines in triethylamine as functions of temperature. (Coordinate scales similar to those recommended by A.S.T.M.; see reference 11.)

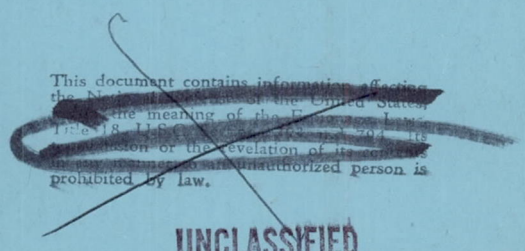
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